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**DEVELOPMENT OF A SEMI-INDUSTRIAL
DEHYDRATION SYSTEM FOR SMALL PRAIRIE
FRUITS AND QUALITY ASSESSMENT**

Funded by: The Agriculture Development Fund

March 2010

Prepared by: University of Saskatchewan (U of S)

FINAL REPORT

**Development of a Semi-Industrial Dehydration System for small Prairie
Fruits and Quality Assessment**

Project # 2006 0152

Final Report

Submitted to the

**Agriculture Development Fund
Saskatchewan Ministry of Agriculture
Regina, Saskatchewan**

By

V. Meda

**Department of Agricultural and Bioresource Engineering
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March, 2010

March 31, 2010

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Re : Final Report: Project: 2006-0152

Dear Dr. Chris,

Attached please find the final report for our ADF Project # 2006-0152. I will be glad to provide any additional information, deemed necessary. Delay in submission of this report is sincerely apologised (I have been on Sabbatical leave since July 1, 2009 until June 30, 2010).

I would like to thank you for your continued support and cooperation.

Sincerely,

Sd/-

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FINAL REPORT

Summary

ADF Project # 2006-0152

DEVELOPMENT OF A SEMI-INDUSTRIAL DEHYDRATION SYSTEM FOR SMALL PRAIRIE FRUITS AND QUALITY ASSESSMENT

Saskatchewan fruit industry continues to diversify. The cherry group (CCPI) is rapidly moving forward in terms of identifying the site for a central processing facility, research potential, export market, and formulating new strategies in terms of export potential and value-added processing. At present, we do not have even a single commercial fruit dryer to meet the needs of an individual producer/processor. This is the first project funded by ADF related to the development of a semi-industrial scale fruit dehydration/dryer system in Saskatchewan.

In Collaboration with the Industry (Riverbend Plantations Inc.), we were able to reach an agreement that we leased the EnWave™ NutraRev Dryer that was installed at the processing facilities, near Saskatoon. Our significant research trials took place at the processing site and closer to the cold room environment.

All the planned (scheduled) drying tests and material characterization were completed. An optimisation study was also conducted in addition to the proposed study and the findings have been published at an International journal (Drying Technology, see attached).

Tasks Identified and Status of the Research Project:

1. Thorough literature review conducted on methods of drying and processing small fruits, particularly the saskatoon berries, cherries, etc. The list of references included in the report is a partial listing.
2. Material characterization studies and physical-chemical properties measurement of the osmotic medium (corn syrup, HFCS and sugar) and the fruit sample conducted
3. Drying experiments conducted using Microwave, Convective and Microwave, Microwave and Vacuum Combination and Cross flow thin layer systems, with in the Bioprocess Engineering Research laboratories, at UofS and some tests at the processing facilities site.

Personnel:

Highly qualified personnel (such as graduate research associate, Post-doctoral fellow, summer research students) were hired to look into developing standard drying methodology, conduct experimental work and analyse data and dissemination aspects (conference, publication).

One summer student was hired during the summer (2007, 2008) and a research associate (Dr. P Mitra) was recruited to work for Summer 2008 and beyond.

Selected fresh and frozen berries were dried in 2007 and 2008 however the preliminary data obtained was useful for further experimental work, being carried out, presently. The findings were compared to the data obtained in 2008 and 2009. We were able to investigate if there were any varietal differences, If any, that would be significant or not.

Industry Collaboration:

Riverbend Plantations Inc. (Collaborating Industry) has been in regular contact on regarding the needs /problems associated with the fruit drying system and the industry.

Microwave Vacuum Dryer (En-WaveTM), an experimental Freeze dryer, MW-InfraRed dryer (modified to suit our instrumentation and controls from GETM), MW-Convective Ovens, and most of all the analytical tools, required for this study. Information on drying kinetics, thermal-profiles, design and end-product quality assessment is not currently available in literature for fruits such as Saskatoon berries, sour cherries, buffaloberries, haskap and sea-buckthorn). I recognise this will be the first study on an attempt to commercially build the dryer system for Prairie small fruits (saskatoons, cherries and haskaps).

Most of the drying experiments were carried out in the Department of Agricultural and Bioresource Engineering, University of Saskatchewan, and some were conducted at the Riverbend facilities in Saskatoon. Product quality analysis will be accomplished using other resources as well (Depts. of Food Science and Applied Microbiology and Plant Sciences, College of Agriculture and Bioresources, Co-operation from the Food Development Center (FDC) and laboratories (AAFC), including the Richardson Center for Functional Foods and Nutraceuticals, University of Manitoba.

Budget:

A post-doctoral fellow (PDF) was recruited in Summer 08. Standard salary, as per the University policy, were followed.

Portion of the budget was allocated towards operational expenses for setting up the dryer (EnWave) at the industry premises, running the drying experiments, research materials and supplies, EnWave equipment lease, travel and analysis of nutrition data (specifications) and basic process parameters.

Appendix:

Conference papers and publications (sample listing)

Journal Publications

1. Optimization of Microwave-vacuum Drying Parameters of Saskatoon Berries using Response Surface Methodology (RSM). Drying Technology -2009 (published: see attached).
2. Physical, Mechanical and Structural Properties of Vacuum-assisted Microwave Drying of Saskatoon berries. International Journal of Food Properties- 2009 (will be submitted very soon).
3. Quality characterization and Sorption Isotherm of Microwave Vacuum Dried Saskatoon Berries. Food and Bioprocess Technology-2009 (manuscript under preparation).
4. Effect of different Drying Methods on Retention of Antioxidants and total Phenolic Compounds in Saskatoon berries (research progressing).
5. JMPEE- IMPI Journal Publication (see attached)

Conference Publications (sample list)

Optimization of Drying Parameters of Saskatoon Berries (*Amelanchier alnifolia*) using a Combined Microwave and Vacuum Method. 2009 CIGR International Symposium on Food Processing, Monitoring Technology in Bioprocesses and Food Quality Management (5th CIGR Section VI International Symposium), Aug 31st to Sept 2nd 2009, Potsdam, Germany.

Reccomendation: It is strongly recommended we develop a in-house fruit dryer system to meet the Saskatchewan's growing fruit industry. The research findings have paved paths for many processing outlets to explore developing value-added products for food and nutraceutical industry. Further studies are required to fully optimized the drying parameters and conduct an economic and energy assessment.

Acknowledgement: The authors would like to thank ADF for the grant and technical assistance provided throughout the period. Special acknowledgement goes to Riverbend Plantations Inc. (Grace Whittington) for all the cooperation, materials and useful discussions during this research period. EnWave Corp. is also acknowledged for their timely participation.

Study I: Microwave-vacuum Drying of Saskatoon berries

Drying Material and Method

Material

Saskatoon berries (*Amelanchier alnifolia* Nutt. cv. Smoky and Thiessen), harvested in year 2006 were supplied by the Riverbend Plantation Gourmet Foods (Saskatoon, Saskatchewan, Canada) and were kept under frozen storage until the experiments were conducted. Before carrying out the experiments, berries were thawed in a refrigerator for 24 hours. Moisture content of the samples was determined in a vacuum oven at 103°C for 24 hours. The initial moisture content of the berries ranged from 74.5 to 76.2% wet basis (w.b.)

Equipment

A combined microwave-vacuum dryer, Model VMD 1.8 (Enwave® Corp., Vancouver, BC) shown in Figure 1, was used for the drying of saskatoon berries.

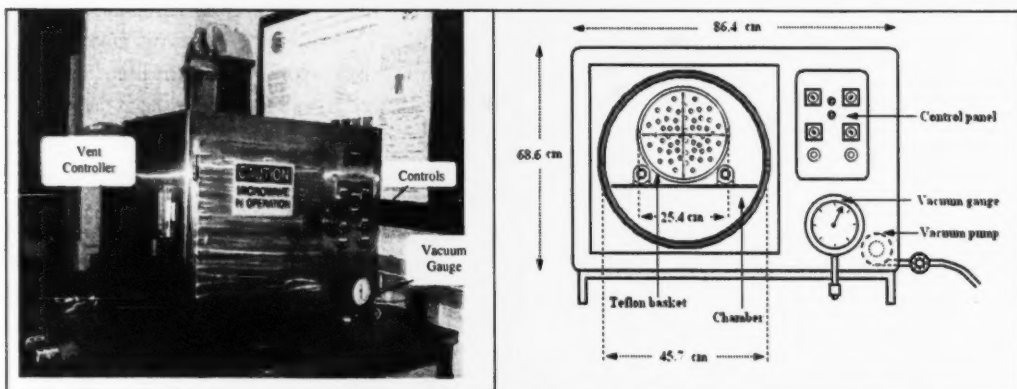


Figure 1. EnWave microwave-vacuum dryer.

Microwave-vacuum drying

About 100 g of saskatoon berries was weighed and placed on a flat glass plate for each drying experiment in the dryer. The desired power level was set and the vacuum pump was turned on. After the desired vacuum pressure has been achieved, the vacuum pump was turned off and the microwave power was turned on. The set vacuum pressure was maintained throughout the drying period. Two vacuum pressure levels of 33.5 kPa (10 inHg) and 67 kPa (20 inHg) were used. Three power levels P10, P7 and P5 corresponding to 745, 514 and 374 W, respectively, were used.

Color measurement

The color of the samples was measured using Hunterlab Color Analyzer (Hunter Associates Laboratory Inc., Reston, Virginia, U.S.A.) shown in Figure 2. The chromacity of microwave-vacuum dried berries was determined by measuring their respective L, a and b coordinates.



Figure 2. HunterLab color analyzer.

Water activity

Water activity (a_w) of the saskatoon berries was measured using a Pawkit water activity meter (Decagon Devices, Inc., Pullman, WA, U.S.A.).

Results

Drying curve

Figure 3 shows the drying curves for microwave-vacuum drying of saskatoon berries at different microwave power and vacuum pressure levels.

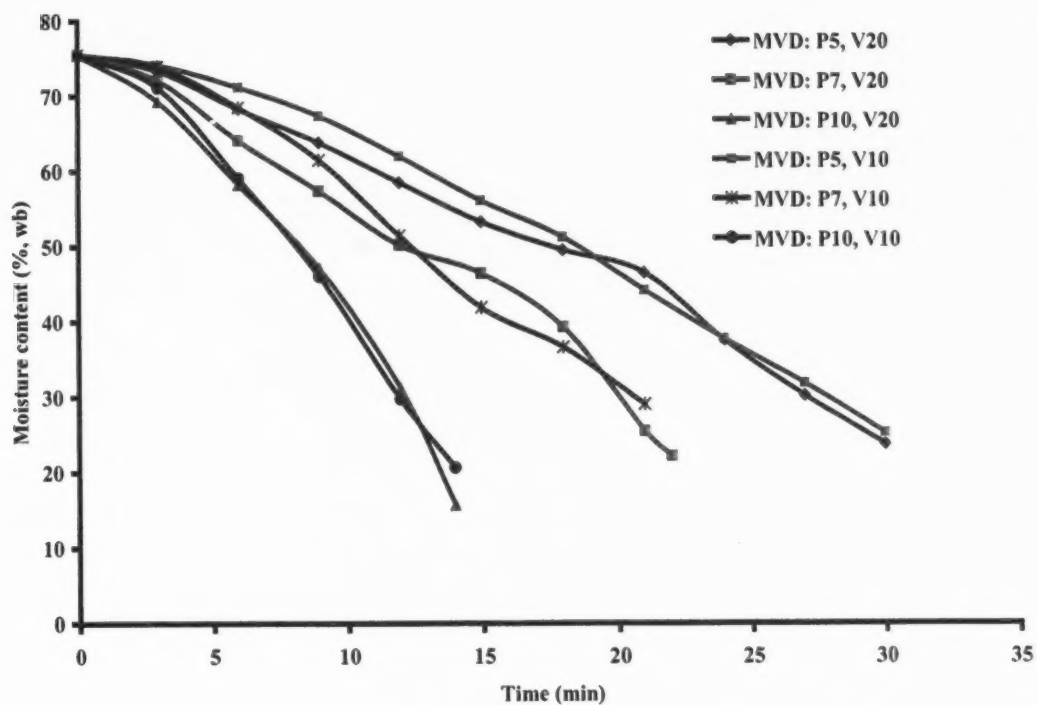


Figure 3. Drying curves of saskatoon berries at different of microwave power and vacuum pressure levels.

Figure shows the picture of dried saskatoon berries at power level 10 and vacuum level 20.



Color parameters

The color parameters (L, a, b) for the saskatoon berries before and after drying, delta values (color change) and the total colour difference are presented in Table 2. There were variations in the L and a values for the fresh berries. The differences in the b values for the fresh berries were not significant at 5% level. After drying the samples did not show any significant variation in the a values. However, the samples exhibited some variations in the L and b values after drying.

Table 1. Comparison of color parameters for microwave-vacuum drying of saskatoon berries at various conditions of microwave power level and system pressure.

Microwave power level	Vacuum pressure (kPa)	Color parameters						Delta values			ΔE_{ab}
		Fresh berries			Dried berries						
		L	a	b	L	a	b	ΔL	Δa	Δb	
P10	33.5	10.69a	3.84b	1.62a	13.23a	1.34a	0.54a	2.54abc	-2.50a	-1.09a	4.15b
P7	33.5	14.03b	3.00ab	1.57a	16.37b	1.99a	1.25b	2.34abc	-1.02ab	-0.32a	3.32ab
P5	33.5	11.59a	3.10ab	1.87a	16.17ab	2.02a	1.19bc	4.58c	-1.08ab	-0.68a	4.91b
P10	67.0	16.21c	2.45ab	1.17a	15.30ab	1.72a	0.91ab	-0.92a	-0.73b	-0.26a	2.76ab
P7	67.0	14.02b	2.46ab	1.29a	18.07b	1.41a	1.15bc	4.05bc	-1.05ab	-0.14a	4.23b
P5	67.0	15.64bc	2.03a	1.48a	15.88ab	1.71a	1.36c	0.25ab	-0.32b	-0.12a	0.98a

L = brightness (+100)/ darkness (+0); a = redness (+50)/greenness (-50); b = yellowness (+50)/blueness (-50).

Water activity

The change in water activity on microwave-vacuum drying of saskatoon berries under different experimental conditions is listed in Table 3. Water activity values of the samples were reduced from initial 0.93 to a range of 0.61 - 0.75. The highest a_w value of 0.75 was obtained at P7 and vacuum pressure of 67.0 kPa. There was no correlation between the moisture content and the water activity of the samples. Also temperature did not show any relationship with the water activity.

Table 3. Water activity values comparison of fresh and dried saskatoon berries.

Sample		Temperature (°C)	Water activity (a_w)	Moisture content (%)
Fresh Berries		24.3	0.93 (0.01)	75.57
Microwave-vacuum drying				
Microwave power level	Pressure (kPa)			
P10	33.5	25.7	0.70	20.68
P10	67.0	26.0	0.66	15.68
P7	33.5	25.4	0.73	29.03
P7	67.0	25.8	0.75	25.49
P5	33.5	25.2	0.74	25.28
P5	67.0	26.0	0.61	23.75

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Study II: Microwave-vacuum drying and storage stability of cherries at room temperature: Preliminary study

Drying Material and Method

Material

Cherries were obtained from Dr. Bob Bors of Plant Sciences Department, University of Saskatchewan, Saskatoon, Sk and were kept under frozen storage until the experiments were conducted. Before carrying out the experiments, berries were thawed in a refrigerator for 24 hours. Moisture content of the samples was determined in a vacuum oven at 103°C for 24 hours. The initial moisture content of the berries was 81.1% wet basis (w.b.).

Microwave-vacuum drying

A combined microwave-vacuum dryer, Model VMD 1.8 (Enwave® Corp., Vancouver, BC) was used to dry the cherries to two final moisture contents of 9.4 and 34.6%, respectively. The samples were dried at microwave power of 374 W and vacuum pressure of 33.5 kPa (10 inHg). The samples were vacuum-packaged after drying and stored at room temperature (22 to 24°C). The samples were inspected for microbial growth every 3 days.

Results

Drying curve and storage stability

Figure 1 shows the drying curves for microwave-vacuum drying of cherries at microwave power of 374 W and vacuum pressure of 33.5 kPa..

After 3 to 4 weeks of room temperature storage, microbial growth was detected on the sample dried to a higher moisture content of 34.6% compared 9.4%. Microbial growth has not been detected on the sample dried to 9.4% till present (about 16 weeks).

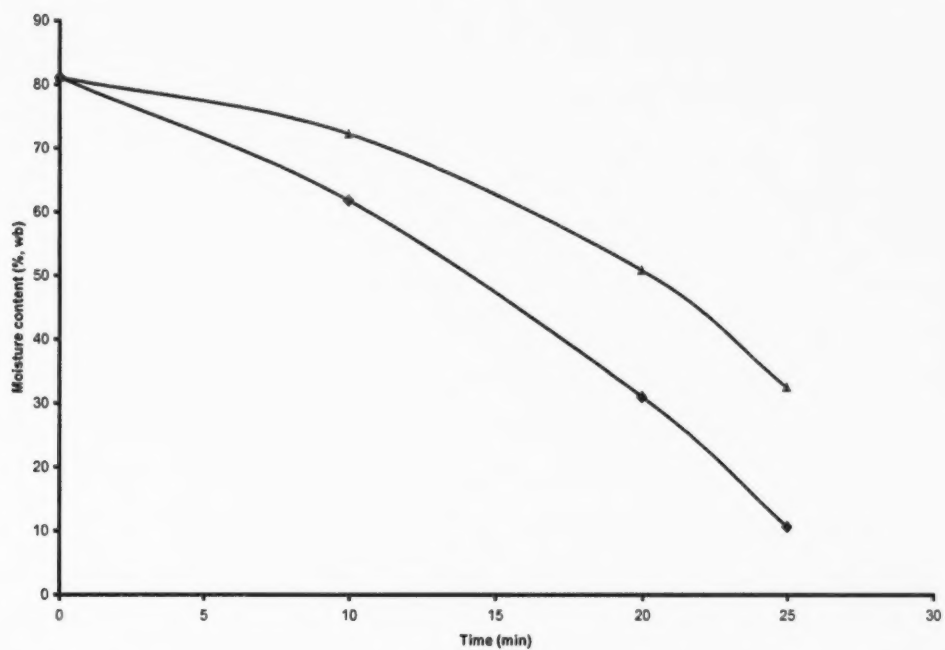


Figure 1. Drying curves of cherries dried at microwave power of 374 W and vacuum pressure of 33.5 kPa.

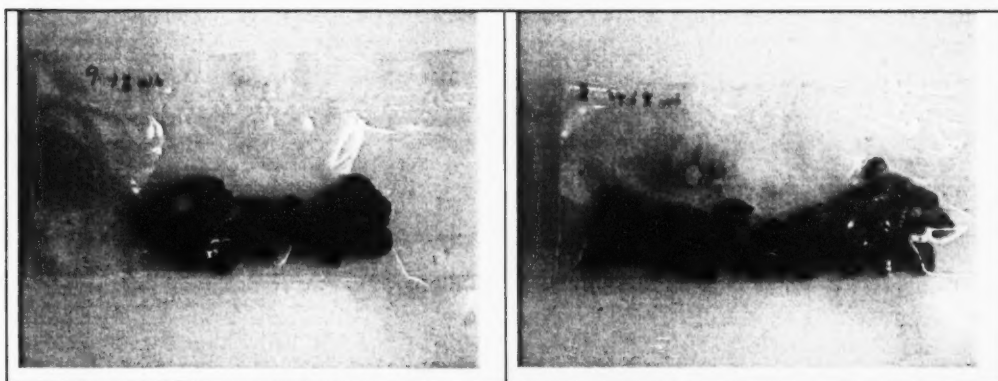


Figure 2. Pictures of cherries microwave-vacuum dried to 9.4 and 34.6%.

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Optimization of Microwave-Vacuum Drying Parameters of Saskatoon Berries Using Response Surface Methodology

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Optimization of Microwave-Vacuum Drying Parameters of Saskatoon Berries Using Response Surface Methodology

Pranabendu Mitra and Venkatesh Meda

Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada

A combined microwave and vacuum system was used to dry the Saskatoon berries (*Amelanchier alnifolia*). A central composite rotate design and response surface methodology were used to determine the influence of process variables (microwave power, drying time, and fruit load) and arrive at optimal processing conditions to reduce the moisture content and water activity of the berries to a safe level. It is concluded that the yield of moisture content and water activity can be reduced to 20% and 0.50, respectively, for microwave power 5.7–6 kW, drying time 51.5–55 min, and fruit load 10–9.75 kg.

Keywords Microwave-vacuum drying; Response surface methodology; Saskatoon berries dehydration

INTRODUCTION

Saskatoon berries (*Amelanchier alnifolia*) possess food value as well as nutraceutical value and have a strong commercial potential. Saskatoon berries were consumed as a food source by the native Canadian and Northern people and early settlers in these areas. They used to eat the sun-dried and smoke-dried Saskatoon berries to flavor foods. The Saskatoon berry juice was popular with the Canadian aboriginal people for the treatment of stomach ailment. They also used to prepare eye- and eardrops from the mature Saskatoon berries.^[1,2] The Saskatoon berries are a rich source of antioxidants because they contain anthocyanins and other phenolic compounds.^[3] Saskatoon berries carry free radical scavenging capacities and they can potentially be used in food products.^[2] Relatively large amounts of minerals (potassium, iron, magnesium, and phosphorous) are found in Saskatoon berries. The berries are considered as a good source of vitamins. They contain vitamin C, thiamin, riboflavin, pantothenic acid, vitamin B-6, vitamin A, and vitamin E.^[1] A food company, Riverbend Plantation Gourmet Foods (Saskatoon, Canada), is producing a wide array of Saskatoon berry food products and has established local and international markets for processed products such as

jam, jelly, and chocolate made with Saskatoon berries. The fresh Saskatoon berries have 80–84% moisture content. The berries are highly perishable fruits and have a very short shelf life. Immediate preservation of the berries after harvest is required for extension of their shelf life. This poses a problem to preserve such highly perishable berries and there is a need to introduce a sustainable preservation system that ensures their shelf life extension and maintains the quality of the berries. Freezing and frozen storage of Saskatoon berries are typically practiced in the Riverbend Plantation Food Company. However, this system needs a large space for storage and transportation is a problem due to high volume and weight. Storage of frozen berries is also a cost-ineffective and energy-intensive process.^[4] This has led to increased interest in alternative preservation methods such as drying.

Drying is the oldest and most cost-effective means of preservation for grains and all varieties of foods. The reason for drying is to reduce the moisture content of the products to a safe level and thus to minimize the deterioration of the quality of the product during storage and to increase the economic return. There are many conventional drying methods in practice to dry fruits and vegetables but there is also concern about quality of the dried products and drying efficiency. The most common conventional drying method used for food materials is hot air drying. The surface of food materials being dried in hot air is exposed for a length of time to elevated drying temperatures, which causes substantial deterioration of quality attributes such as color, nutrients, flavor, and texture.^[5,6] In conventional drying methods, the rate of water evaporation is faster than the rate of water movement to the product surface due to rapid drying and uneven heat transfer into the products and it creates a hard outer skin on the products. This phenomenon is known as *case hardening*, which gives an imbalanced drying quality of the products.^[7,8] Therefore, alternative, energy-efficient drying systems are necessary for the food industry to ensure that high-quality products be developed. Microwave drying has become popular as an alternative drying method in the food industry in recent years.

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Microwave drying is rapid, more uniform, and energy efficient compared to conventional hot air drying.^[8] Microwaves dryers produce electromagnetic radiation of frequencies from several hundred megahertz (500 MHz) to several hundred gigahertz (300 GHz). Microwaves, by virtue of their high frequency, have extremely short wavelengths.^[9,10] The materials can absorb the microwave energy directly and internally and convert it into heat inside the materials, which is known as *volumetric heating*. In microwave drying, the heat is generated throughout the materials, whereas the heat must diffuse in from the surface to the interior in conventional drying. Microwave drying occurs because of vapor pressure difference between interior and surface areas, which accelerates a driving force for moisture transfer.^[7,10,11] This phenomenon may cause rapid drying and overcome the case hardening problem. The vacuum allows the high-energy water molecules to diffuse to the surface and evaporate at a lower temperature than under atmospheric conditions. This generates large vapor pressure gradients and accelerates the drying rates.^[12] Therefore, the materials can be dried at low temperature and need a shorter drying period. Moreover, the absence of air during drying diminishes oxidation. These factors improve the quality attributes (i.e., color, texture, flavor, and nutrients) of the dried products.^[8] Kwok et al.^[13] studied microwave drying of Saskatoon berries and they showed that the berries dried using microwave-vacuum dehydration exhibited higher total anthocyanin and phenolic levels, which were associated with a greater antioxidant activity, compared to air-dried berries. A study on the comparison among different drying methods showed that the carotene retention of carrot slices and the vitamin C retention of apple slices dried by the microwave-vacuum method were close to those of freeze-dried carrot and apple slices and much better than those of conventional hot air-dried ones.^[14] The microwave-vacuum drying process significantly reduces drying time compared to conventional methods of drying and energy consumed is less than freeze drying.^[15] Hence, microwave-vacuum drying has proved to be an attractive drying method for high-quality dried products. In addition, it improves the energy efficiency.^[5,8] However, if microwave drying process variables are not applied properly, it gives poor-quality products.^[8] For a microwave-vacuum drying system, there is a need to optimize the process variables such as microwave power, drying time, and weight of the dehydrator for minimizing the moisture content and water activity to a safe level.

A statistical experimental design based on central composite rotate design (CCRD) and a response surface methodology (RSM) can be an effective option for the optimization of microwave-vacuum drying parameters.^[16,17] The CCRD and RSM are the processes that combine mathematics with statistics and are useful to model and analyze in applications

where several factors control a response (output) of interest.^[16,18] The objective of this study is to optimize the microwave-vacuum process variables, microwave power, drying time, and fruit load, in order to reduce the moisture content and water activity of the Saskatoon berries to a safe level to assure an extension of their shelf life.

MATERIALS AND METHODS

Materials

Riverbend Plantation (Saskatoon, Saskatchewan, Canada) supplied the frozen Saskatoon berries (*Amelanchier alnifolia* Nutt. cvs. Smoky and Thiessen) in bulk. The frozen berries were kept in cold storage in the Riverbend Plantation. Prior to microwave-vacuum drying, the frozen berries were thawed using a predryer to equilibrate with ambient conditions and to remove the frozen surface water of the berries. The berries were spread on the surface of the predryer in a single layer and thawed at approximately 40°C for 30 min. The berries were then placed in a perforated ultra-high-density polyethylene (UHDPE) basket to drain out the surface water of the berries. A sample was taken from each treatment and used to determine the moisture content of the fruit prior to drying.

Experimental Design of Microwave-Vacuum Drying

A CCRD was used to study the effect of microwave-vacuum drying variables on the moisture content and water activity of Saskatoon berries. The three input variables were microwave power (5.07–6.93 kW, X_1), drying time (46.5–63.5 min, X_2), and fruit load (9.60–10.40 kg, X_3) and the five levels chosen were -1.68, -1, 0, +1, and +1.68 as shown in Table 1. The input variables and their ranges were selected on the basis of the preliminary experiments avoiding that any experimental point get burn. The experimental design consisted of a total of 20 experimental runs ($n = 2^k + 2k + m$, where, n = total experimental points, input variables, $k = 3$, and central point, $m = 6$), which included eight factorial points, six axial points, and six replicated central points^[19] as shown in Table 2.

Microwave-Vacuum Drying of Saskatoon Berries

An industrial-scale microwave-vacuum dryer (Model MG8 KW, Enwave Corporation, Vancouver, Canada) at Riverbend Plantation (as shown in Fig. 1) was used to dry the Saskatoon berries. The dryer consisted of a cylindrical stainless steel chamber, where the microwave field and vacuum were applied. Inside the chamber, berries were contained in a basket made of UHDPE, sitting on two rollers, also made from UHDPE. One of the rollers was connected directly to a variable motor through the chamber wall. The cogs in the wall of the basket mesh matched the cogs in the roller to provide smooth rotation. Basket rotation speed was set prior to each drying cycle and the speed was kept constant at 10 rpm for all the drying

TABLE 1

Treatments levels and coded values for each of the independent variables used in developing the experimental data to optimize the microwave-vacuum drying parameters of Saskatoon berries

Independent variable	Symbols		Levels	
	Uncoded	Coded	Uncoded	Coded
Microwave power (kW)	P	X_1	5.07	-1.68
			5.5	-1
			6.0	0
			6.5	1
			6.93	1.68
Drying time (min)	t	X_2	46.5	-1.68
			50	-1
			55	0
			60	1
			63.5	1.68
Fruit load (kg)	W	X_3	9.60	-1.68
			9.75	-1
			10.0	0
			10.25	1
			10.40	1.68

$$X_1 = (P - 6)/0.5, X_2 = (t - 55)/5, X_3 = (W - 10)/0.25.$$

treatments. Vacuum was provided by an external pump and vacuum pressure was kept constant (near to 100 kPa) for all the drying treatments. The desired power level of microwave was set and supplied energy to the berries in the vacuum chamber to generate the drying process. The drying was continued to the desired treatment period. After completion of microwave-vacuum drying, the dried berries were taken out and cooled to room temperature. The dried samples were then kept in a refrigerator until analysis. In order to optimize the drying conditions, dehydration was performed for different drying conditions as shown in Table 2. Texture of fruit product can be varied to match the end use of the product. Depending on the treatment power level and duration, finished products can be created that are anywhere from dry and crunchy to chewy in texture. Microwave-vacuum drying control is a significant difference from freeze drying, where essentially all of the water is removed. The effect of the vacuum minimizes volume loss during drying and provides a puffy texture of the dried products.

Determination of Moisture Content of Dried Berries

Moisture content of dried berries was determined by an oven drying method.^[20] The samples of dried berries (5 g)

TABLE 2

Experimental design and results (moisture content and water activity) of microwave-vacuum drying of Saskatoon berries

Treatment	Microwave power, P (kW)	Drying time, t (min)	Fruit load, W (kg)	Final moisture content (% wb)	Water activity (a_w)
	X_1	X_2	X_3		
1	5.5 (-1)	50 (-1)	9.75 (-1)	44.15 ± 1.55	0.847 ± 0.006
2	5.5 (-1)	50 (-1)	10.25 (1)	47.44 ± 1.50	0.891 ± 0.006
3	5.5 (-1)	60 (1)	9.75 (-1)	32.35 ± 0.98	0.763 ± 0.006
4	5.5 (-1)	60 (1)	10.25 (1)	43.67 ± 1.18	0.827 ± 0.006
5	6.5 (1)	50 (-1)	9.75 (-1)	32.88 ± 0.59	0.763 ± 0.021
6	6.5 (1)	50 (-1)	10.25 (1)	45.37 ± 0.63	0.847 ± 0.010
7	6.5 (1)	60 (1)	9.75 (-1)	8.14 ± 0.23	0.220 ± 0.010
8	6.5 (1)	60 (1)	10.25 (1)	14.35 ± 1.14	0.453 ± 0.011
9	6.0 (0)	55 (0)	10 (0)	35.92 ± 0.76	0.783 ± 0.011
10	6.0 (0)	55 (0)	10 (0)	36.72 ± 1.05	0.783 ± 0.011
11	6.0 (0)	55 (0)	10 (0)	36.49 ± 1.23	0.781 ± 0.017
12	6.0 (0)	55 (0)	10 (0)	37.54 ± 0.62	0.786 ± 0.006
13	6.0 (0)	55 (0)	10 (0)	36.78 ± 0.15	0.783 ± 0.06
14	6.0 (0)	55 (0)	10 (0)	36.04 ± 1.55	0.782 ± 0.006
15	5.07 (-1.68)	55 (0)	10 (0)	52.44 ± 0.72	0.903 ± 0.011
16	6.93 (1.68)	55 (0)	10 (0)	22.01 ± 0.42	0.650 ± 0.000
17	6 (0)	46.5 (-1.68)	10 (0)	49.92 ± 1.33	0.893 ± 0.010
18	6 (0)	63.5 (1.68)	10 (0)	16.94 ± 0.13	0.550 ± 0.000
19	6 (0)	55 (0)	9.60 (-1.68)	30.02 ± 0.45	0.747 ± 0.006
20	6 (0)	55 (0)	10.40 (1.68)	40.11 ± 0.78	0.810 ± 0.010

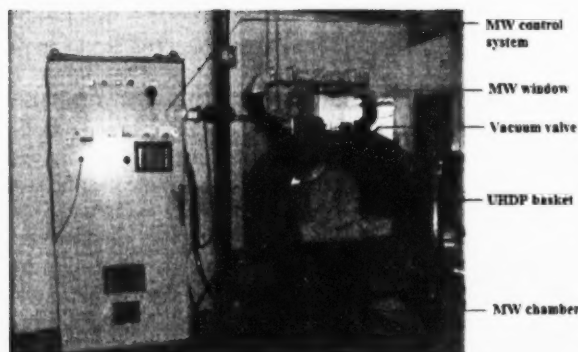


FIG. 1. Microwave-vacuum dryer used in this study (located at Riverbend Plantation).

were placed in a convection oven and dried at 105°C for 24 h. The moisture content of dried berries was expressed in percentage on a wet basis (wb). All the measurements were done in triplicate.

Determination of Water Activity of Dried Berries

A Pawkit water activity meter (Decagon Devices, Inc., Pullman, WA) was used to determine the water activity of the dried Saskatoon berries. The water activity meter consists of a dielectric humidity sensor to measure the water activity of samples and the equipment can determine the water activity of a sample with a very small variation (± 0.02). The sample temperature influences water activity measurements. The accuracy is best when the temperature of the samples is stable near room temperature. The dried samples were kept in the laboratory at room temperature ($23 \pm 1^\circ\text{C}$) prior to measuring the water activity of the dried berries. The water activity measured temperature was maintained at $23 \pm 1^\circ\text{C}$ for all the measurements. All measurements were done in triplicate.

Regression Modeling and Statistical Analysis

A second-order polynomial equation was used to fit the coded variables (as shown in Table 1):

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 + B_{12}X_1X_2 + B_{23}X_2X_3 + B_{13}X_1X_3 \quad (1)$$

where Y represents the experimental response; B_0 , B_1 , B_2 , B_3 , B_{11} , B_{22} , B_{33} , B_{12} , B_{23} , and B_{13} were constants and regression coefficients, respectively, of the model; and X_1 , X_2 , and X_3 were the independent drying process variables. The whole model included linear, quadratic, and cross-product terms as shown in Eq. (1), which explained the effect of all three variables on the response Y .

The CCRD experimental design was combined with the response surface methodology (RSM) to solve the regression equation and investigate the effects of three independent drying process variables of microwave power (kW), drying time (min), and fruit load (kg) to arrive at the optimal conditions to select the drying parameters for a safe level of moisture content and water activity of the berries. Statistical analyses were performed using computer software SAS 9.1.

RESULTS AND DISCUSSION

Experimental Results of Microwave-Vacuum Dehydration of Saskatoon Berries

The experimental data of three factors (microwave power, drying time, and fruit load) and five levels employed for the central composite rotate design are shown in Table 1. The experimental design and results (moisture content and water activity) for Saskatoon berries drying under the 20 experimental conditions are shown in Table 2. The lowest yields of moisture content and water activity (a_w) were 8.14% and 0.22, respectively, and were obtained after 60 min drying at 6.5 kW and 9.75 kg. However, moisture content and water activity increased to 14.35% and 0.453, respectively, when fruit load was increased from 9.75 kg to 10.25 kg with the same microwave power (6.5 kW) and drying time (60 min). This was due to the fact that the higher fruit load contained higher water mass than the lower fruit load and it affects the reduction of moisture content and water activity in the final dried berries at the same operating conditions of microwave power and drying time. Moisture content decreased from 52.44 to 22.01% and water activity decreased from 0.903 to 0.650 when microwave power was increased from 5.07 to 6.93 kW in the same operating conditions of drying time (55 min) and fruit load (10 kg). It indicated that microwave power had a great influence in accelerating the reduction of moisture content and water activity of the Saskatoon berries. This phenomenon can be interpreted as the high microwave energy being absorbed by the dipole molecules available in the berries and the high absorbed microwave energy generating heat to increase the drying rate and mass transfer being dominated by vaporization.^[20] The results also show that the drying time played an effective role in reducing the moisture content and water activity of the berries. When drying time increased from 46.5 to 63.5 min in the drying operation of microwave power (6 kW) and fruit load (10 kg), the moisture content and water activity of the berries decreased 49.92–16.94% and 0.893–0.550, respectively. Overall observations of the results show that the moisture content and water activity generally decreased with the microwave power and drying time and were inversely related to fruit load in the microwave-vacuum drying process of Saskatoon berries.

Fitting the Regression Model

The developed regression models for the relationship between moisture content yield (Y_{moisture}) and the coded values (Eq. (2)) and between water activity (Y_{aw}) and coded values (Eq. (3)) of independent variables of microwave power (X_1), drying time (X_2), and fruit load (X_3) and their interactions are shown below:

$$Y_{\text{moisture}} = 36.64 - 8.65X_1 - 9.29X_2 + 3.68X_3 - 0.11X_1^2 - 1.46X_2^2 - 0.88X_3^2 - 5.02X_1X_2 + 0.22X_2X_3 + 0.51X_1X_3 \quad (2)$$

$$Y_{\text{aw}} = 0.78 - 0.11X_1 - 0.12X_2 + 0.04X_3 - 0.01X_1^2 - 0.03X_2^2 - 0.01X_3^2 - 0.10X_1X_2 + 0.02X_2X_3 + 0.03X_1X_3 \quad (3)$$

The significance of each coefficient and their interactions was determined using the t-test (t value). The linear terms of microwave power (X_1), drying time (X_2), and fruit load (X_3); the second-order term of X_2^2 ; and the cross-product term between microwave power and drying time (X_1X_2) gave highly significant effects on the yields of moisture content and water activity of the berries having higher absolute t value than critical t value of 2.26 (at p value <0.05 and degrees of freedom = 9). The coefficients are highly significant with an absolute t value higher than critical t value because the t value needs to be equal or exceed the critical t value for the null hypothesis to be rejected.^[19] The second-order terms of X_1^2 and X_3^2 and cross-product terms of X_2X_3 and X_1X_3 did not show a highly significant effect on the yields of moisture content and water activity of the berries achieving absolute t value less than critical t value.

Analysis of variance (ANOVA) results of the models are shown in Table 3, indicating a good model performance (with an R^2 value of 0.98 and an F value of 65.80 for moisture content yield and with an R^2 value of 0.94 and an F value of 18.15 for water activity yield) among linear,

quadratic, cross-product, and total model. Interactions among the variables are not negligible. The R^2 is one of the measures of degree of fit of a model. The model R^2 values of 0.98 (for moisture content yield) and 0.94 (for water activity yield) imply that the variations of 98% for moisture content yield and 94% for water activity yield of microwave-vacuum drying can be attributed to the independent variables of microwave power, drying time, and fruit load.

The plots of the experimental values of moisture content yield versus predicted values (Eq. (2)) and the experimental values of water activity yield versus predicted values (Eq. (3)) are shown in Figs. 2 and 3. The plots showed a close fit of the observed values with the predicted ones. Thus, a statistically significant multiple regression relationship between the independent variables (X_1 , X_2 , and X_3) and the response variable (Y) can be established. The second-order polynomial model showed a good fit and effectively represented the relationship among the parameters selected.

Response Surface Analysis

The three-dimensional plots of the response surfaces are presented in Figs. 4–7 by presenting the response as function of two factors and keeping the third constant. Figures 4 and 6 reveal the effects of microwave power and fruit load on moisture content yield and water activity yield of microwave-vacuum drying of Saskatoon berries. A linear effect of microwave power and an inversely linear effect of fruit load on the responses were found. Figures 5 and 7 show the effects of drying time and fruit load on moisture content yield and water activity yield of microwave-vacuum drying of Saskatoon berries. The results indicate that the drying time has a linear effect, whereas the fruit load has an inversely linear effect on moisture content and water activity of microwave-vacuum dried Saskatoon berries. Therefore, the moisture content and water activity of Saskatoon berries decreased with

TABLE 3
Analysis of variance (ANOVA) of the regression parameters for the response surface model for microwave-vacuum drying of Saskatoon berries

Response	Regression	df	Type I sum of squares	R-square (R^2)	F value	Pr > F
Moisture content	Linear	3	2382.63	0.89	179.14	<.0001
	Quadratic	3	38.51	0.01	2.90	0.0882
	Cross-product	3	204.38	0.08	15.37	0.0004
	Total model	9	2625.52	0.98	65.80	<.0001
Water activity	Linear	3	0.381	0.74	42.61	<.0001
	Quadratic	3	0.019	0.04	2.14	0.1581
	Cross-product	3	0.087	0.17	9.71	0.0026
	Total model	9	0.487	0.94	18.15	<.0001

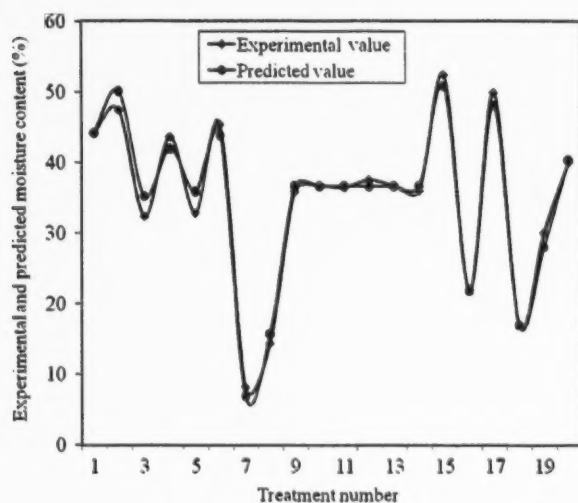


FIG. 2. Comparison between experimental and predicted yields of moisture content (% wb) of dried Saskatoon berries.

the increase of both the microwave power and the drying time, whereas the fruit load had a negative effect on the reduction of moisture content and water activity of Saskatoon berries during the microwave-vacuum drying of the fruits. The response surfaces show a similar trend for both of moisture content and water activity, which indicates a correlation between moisture content and water activity.

Optimum Operating Conditions of Microwave-Vacuum Drying

Regression model Eq. (2) was used to determine the optimum processing conditions for moisture content yield

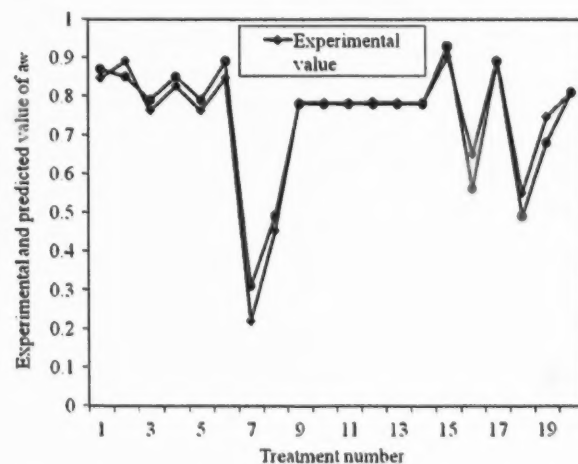


FIG. 3. Comparison between experimental and predicted water activity (a_w) of dried Saskatoon berries.

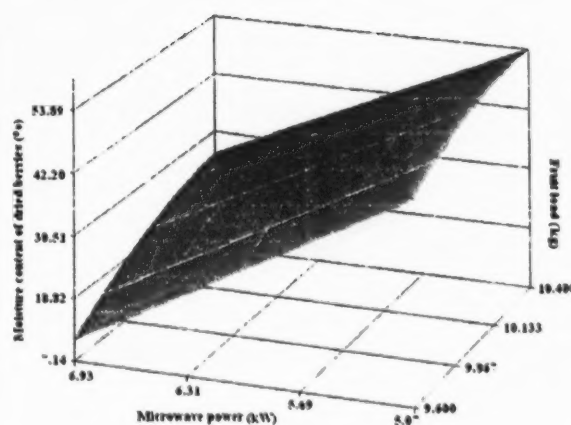


FIG. 4. Response surface plot of the microwave vacuum drying of Saskatoon berries for the effects of microwave power (kW) and fruit load (kg) on moisture content.

of microwave-vacuum drying of Saskatoon berries. The values of independent variables (X_1 , X_2 , X_3) were determined and response was calculated at the optimum point. In order to get these optimum values, first the partial derivatives of the regression Eq. (2) were obtained with respect to X_1 , X_2 , and X_3 , respectively, and they were set to zero^[22] to get the three equations given below:

$$-0.22X_1 - 5.02X_2 + 0.51X_3 = 8.65 \quad (4)$$

$$-5.02X_1 - 2.92X_2 + 0.22X_3 = 9.29 \quad (5)$$

$$-0.51X_1 - 0.22X_2 + 1.76X_3 = 3.68 \quad (6)$$

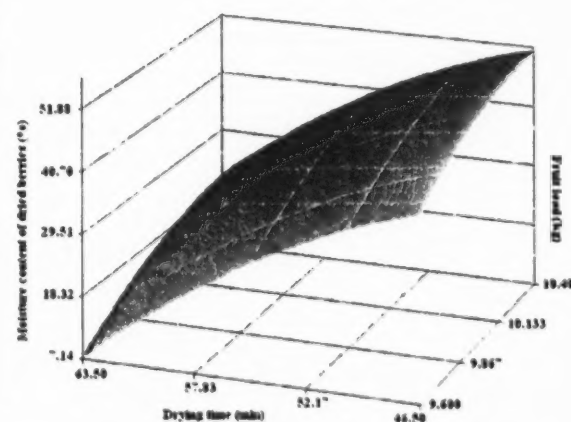


FIG. 5. Response surface plot of the microwave vacuum drying of Saskatoon berries for the effects of drying time (min) and fruit load (kg) on moisture content.

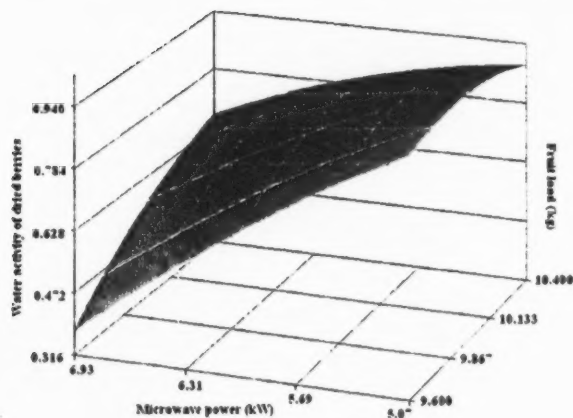


FIG. 6. Response surface plot of the microwave vacuum drying of Saskatoon berries for the effects of microwave power (kW) and load (kg) on water activity (a_w).

By solving Eqs. (4), (5), and (6), the optimum drying point, called the *stationary point*, was obtained for the moisture content yield, and the corresponding values of independent variables at this point in coded form were $X_1 = -0.89$, $X_2 = -1.51$, and $X_3 = 1.63$; the corresponding experimental parametric values were 5.56 kW (optimum microwave power), 47.5 min (optimum drying time), and 10.40 kg (optimum fruit load), respectively; and the predicted moisture content yield at the optimum point was 50.6%.

Similarly, regression model Eq. (3) was used to determine the optimum processing conditions for water activity yield of microwave-vacuum drying of Saskatoon berries. In order to get these optimum values, first the partial derivatives of the regression Eq. (3) were derived with respect to

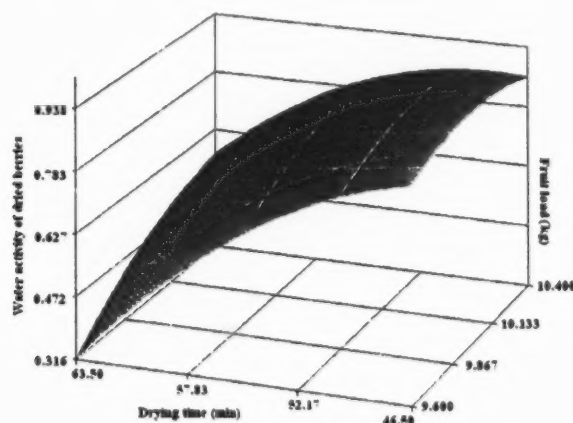


FIG. 7. Response surface plot of the microwave vacuum drying of Saskatoon berries for the effects of drying time (min) and fruit load (kg) on water activity (a_w).

X_1 , X_2 , and X_3 , respectively, and they were set to zero to get the three equations.

By solving the three equations derived from Eq. (3), the optimum drying point for water activity was obtained. The corresponding values of independent variables at this point in coded form were $X_1 = -0.61$, $X_2 = -0.93$, and $X_3 = 0.15$; the corresponding experimental parametric values were 5.60 kW (optimum microwave power), 50.4 min (optimum drying time), and 10.04 kg (optimum fruit load), respectively; and predicted water activity yield at the optimum point was 0.87.

Characterization of the Response Surfaces for Moisture Content and Water Activity

The stationary point can be a point of maximum response, minimum response, or a saddle point. The regression equation was transformed to the canonical form and the eigenvalues were determined using a computer program in SAS 9.1. The eigenvalues obtained were 1.82, -0.86 , and -3.41 (for moisture content) and 0.03, -0.01 , and -0.08 (for water activity). The stationary point was a saddle point because the eigenvalues were different in sign. Because the stationary point is a saddle point, the estimated surface does not have a unique optimum. A ridge of minimum responses for variables (moisture content and water activity) analysis is used to determine the region in which the optimum lies. It is concluded that the yield of moisture content and water activity can be reduced to 20% and 0.50, respectively, for microwave power 5.7–6 kW, drying time 51.5–55 min, and fruit load 10–9.75 kg.

CONCLUSIONS

Saskatoon berries were dried using a combined microwave and vacuum system. The lowest yields of moisture content and water activity (a_w) were 8.14% and 0.22, respectively, and were obtained after 60 min drying at 6.5 kW and 9.75 kg. Meanwhile, the highest moisture content (52.44%) and the highest water activity (0.903) were found for 55 min microwave-vacuum drying at 5.07 kW and 10 kg. The results showed that the moisture content and water activity decreased with the microwave power and drying time and were inversely related to fruit load in the microwave-vacuum drying process of Saskatoon berries. A central composite rotate design and response surface methodology were useful to determine the effect of process variables and arrive at optimal processing conditions in microwave-vacuum drying process of Saskatoon berries. The yields of moisture content and water activity of Saskatoon berries were effectively modeled as a function of the independent variables (microwave power, drying time, and fruit load). The optimum operating conditions of microwave-vacuum drying were calculated, but the statistical analysis suggested that the estimated surface does not have a unique optimum. Therefore, it is concluded that

the yield of moisture content and water activity can be reduced to 20% and 0.50, respectively, for microwave power 5.7–6 kW, drying time 51.5–55 min, and fruit load 10–9.75 kg.

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DRYING KINETICS AND QUALITY CHARACTERISTICS OF MICROWAVE-VACUUM DRIED SASKATOON BERRIES

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Saskatoon berry (Amelanchier alnifolia) is a high moisture content fruit crop, harvested at 75-80% moisture content (w.b.) and dried to lower moisture contents for a safe, extended shelf-life and for further usage in food applications. Saskatoon berries were dried from an initial moisture content of 75.5% to around 25% (w.b.) using microwave-vacuum drying. In this study, saskatoon berries were dried at different microwave power levels P10 (745 W), P7 (514 W) and P5 (374 W) and vacuum pressure levels V20 (67.0 kPa) and V10 (33.5 kPa). The vacuum pressure levels did not greatly influence the drying time of the saskatoon berries compared to the microwave power levels. Increasing the microwave power level produced faster drying times for the samples. After 12 min of drying at power level P10, the moisture contents of the samples at vacuum pressures of 33.5 and 67.0 kPa were 29.74 and 31.24%, respectively. However, after drying for 12 min at vacuum pressure of 33.5 kPa, the moisture contents at power levels P10, P7 and P5 were 29.74, 51.41 and 61.95%, respectively. Polynomial and exponential models were fitted to the drying data. The exponential model provided a better fit for the drying data at the lower vacuum pressure, with higher R^2 and lower SE compared to the polynomial model. On the other hand, the polynomial model provided a better fit for the drying data at the higher vacuum pressure. The vacuum pressure and the microwave power levels did not significantly change the yellowness of the samples as indicated by the Δb values. However, microwave-vacuum drying produced significant color changes in the L (white = 100 to black = 0) and a (green = -a to red = +a) values as indicated by ΔL and Δa . Total color difference was dependent on microwave power and vacuum pressure levels. Water activity of the samples after drying ranged from 0.61 to 0.75 for moisture content range of 15.68 to 29.03%.

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INTRODUCTION

Saskatoon berries (*Amelanchier alnifolia*), commonly known as saskatoons, are purplish-blue berries. The saskatoon is a fruit bearing shrub

native to the southern Yukon and Northwest Territories, the Canadian prairies and the northern plains of the United States [Harris, 1972]. Up to nine varieties of saskatoons are reported according to their habitat, flowering and ripening time, growth form and size, color, seediness and flavour for production.

The saskatoon berry is sold fresh under

Keywords: Microwave, vacuum, drying, saskatoon berry, colour, water activity, quality

U-Pick system or sold frozen to processing companies producing saskatoon berry products such as spreads, jams, fruit toppings, syrups, pie fillings, concentrates, purees and dried berries. Over the past two decades, the total production area of all berries and grapes under cultivation has more than doubled [Statistics Canada, Census of Agriculture 2001].

The saskatoon berry is a good source of protein, fat, fibre, calcium, magnesium, manganese, barium, and aluminium [Mazza and Davidson, 1993]. It also provides vitamins A and C. The berries also contain a high phenolic content with recognized composition of anthocyanins. The saskatoon berries are extremely perishable and the shelf-life of fresh saskatoons is less than 12 hours at ambient conditions [Grace Whittington, Executive Director, Riverbend Plantation, Saskatoon, SK, 2007, Personal communication]. Fresh berries require immediate cooling after harvesting to remove the field heat and reduce flavour and moisture loss. Freezing and frozen storage of the berries is a costly and energy-intensive process.

Water activity is an index that measures the vapour pressure of water relative to that of pure water at the same temperature. It is a measure of the amount of free water available for chemical reactions and microbial growth. Yongsawatdigul and Gunasekaran [1996] dried pretreated cranberries to a final moisture content of 15% using microwave-vacuum and hot-air dryers. The cranberries were pretreated with high fructose corn syrup at 30 and 60° Bx. They reported the water activity range of 0.53 to 0.65 at 30° Bx and 0.41 to 0.52 at 60° Bx, respectively. Drouzas and Schubert [1996] indicated that water activity of banana slices ranged from 0.30 to 0.40 for moisture content range of 4.76 to 7.41%.

Microwave and microwave-vacuum combination drying could be a possible alternative to freezing of fresh berries. Microwave-vacuum drying is a rapid and efficient dehydration method that can yield products with unique characteristics and improved quality compared

to conventionally hot-air dried products. The electromagnetic microwave energy penetrates into the interior of the food, where it is converted to thermal energy, providing a rapid heating mechanism.

Vacuum reduces the boiling point of water keeping the product temperature low, as well as creating a pressure gradient that enhances the drying rate. Load size, power level and vacuum pressure influence drying rate. Vacuum drying has been successfully applied to many fruits and vegetables and other heat-sensitive foods. Vacuum dried materials are characterised by better quality and retention of nutrients and volatile aroma [Drouzas and Schubert, 1996; Tein *et al.*, 1998].

Microwave-vacuum dryers have been used by researchers to dry food, pharmaceutical and agricultural products [Drouzas and Schubert 1996; Tein *et al.*, 1998; Jasna *et al.*, 2001; Giri and Prasad, 2007; Berteli *et al.*, 2007; Changrue *et al.*, 2007; Poonnoy *et al.*, 2007; Opoku *et al.*, 2007; Cui *et al.*, 2008]. Drouzas and Schubert [1996] used microwave-vacuum dryer to dry banana slices at different power and vacuum pressure levels. They indicated that microwave-vacuum drying produced products with excellent quality. Microwave-vacuum drying of a pharmaceutical product (hydrochlorthiazide) at a microwave power of 20 W and absolute pressure levels of 50 and 75 mbar was investigated by Berteli *et al.* [2005]. They reported that the microwave-vacuum drying kinetics at both pressure levels showed little difference.

The aim of this present work was to investigate microwave-vacuum drying kinetics and quality characteristics of saskatoon berries. The effects of process variables (power level, vacuum pressure and drying time) on the drying characteristics of berries were considered.

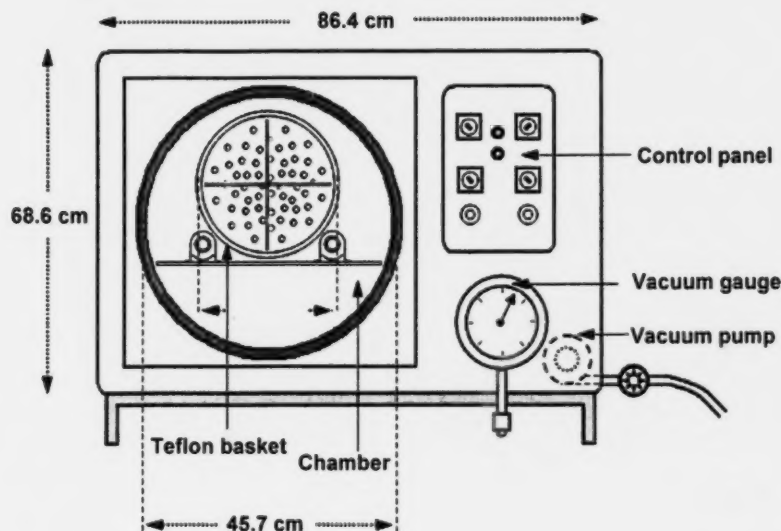


Figure 1. Schematic diagram of the Enwave® microwave-vacuum dryer.

MATERIALS AND METHODS

Materials

Saskatoon berries (*Amelanchier alnifolia* Nutt. cv. Smoky and Thiessen), harvested in the year 2006 were supplied by the Riverbend Plantation Gourmet Foods (Saskatoon, Saskatchewan, Canada) and were kept under frozen storage until the experiments were conducted. Before carrying out the experiments, berries were thawed in a refrigerator for 24 hours. Moisture content of the samples was determined in a vacuum oven at 103°C for 24 hours. The initial moisture content of the berries ranged from 74.5 to 76.2% wet basis (w.b.).

Microwave-vacuum drying

A combined microwave-vacuum dryer, Model VMD 1.8 (Enwave® Corp., Vancouver, BC) shown in Figure 1, was used for the drying of saskatoon berries. The equipment consists of a circular drying chamber, rotating basket, vacuum pump, microwave generating system, a

motor and a venting system. The drying chamber has an internal diameter of 45.7 cm and a length of 46.4 cm. The microwave dryer has 10 power levels with a rated power of 2 kW at 2450 MHz. Vacuum pressure in the chamber is monitored by a vacuum gauge.

About 100 g of saskatoon berries was weighed and placed on a flat glass plate for each drying experiment in the dryer. The desired power level was set and the vacuum pump was turned on. After the desired vacuum pressure was achieved, the vacuum pump was turned off and the microwave power was turned on. The set vacuum pressure was maintained throughout the drying period. Two vacuum pressure levels of 33.5 kPa (10 inHg) and 67 kPa (20 inHg) were used. Three power levels P10, P7 and P5 corresponding to 745, 514 and 374 W, respectively, were used.

The weight of the sample was recorded at 3 min intervals by switching off the microwave power and then releasing the vacuum. It took about 2 min to weigh the sample, adjust the vacuum and turn on the microwave power. The samples were dried until the moisture content

reached within a range of 20-30% (w.b.). The dried samples were placed in resealable plastic bags and stored at 5°C for subsequent moisture and quality parameter measurements.

The variables chosen for the drying experiments were microwave power (P) and vacuum pressure (V). Combinations of microwave power and vacuum pressure levels were selected for the experiments. The experiments for all conditions were done in duplicates.

Modeling drying data

Various drying models have been used to describe the drying kinetics of agricultural and food materials. Researchers have used polynomial and exponential models to describe the drying kinetics of various agricultural materials in convective and microwave-convective drying [Jasna, Sander, & Skansi, 2001; Prabhanjan, Ramaswamy, & Raghavan, 1995; Sharma & Prasad, 2001]. The following two drying models were selected to describe the drying kinetics of saskatoon berries and the microwave-vacuum drying data were fitted to them to test their validity:

$$MR=(a + bt)^2 \quad (1)$$

$$MR=\exp(m+nt^{1.5}) \quad (2)$$

where, MR = moisture ratio = $(M - M_e)/(M_0 - M_e)$, M = moisture content (kg water/kg dry matter) at time t , M_e = equilibrium moisture content (kg water/kg dry matter), M_0 = initial moisture content (kg water/kg dry matter) at time = 0, a and b are constant parameters; m = empirical constant, n = drying rate constant ($\text{min}^{-1.5}$) and t = drying time in min.

For the microwave-vacuum drying data, the equilibrium moisture content (M_e) was assumed to be zero [Maskan, 2000; Soysal, 2004]. The constant parameters in the drying models were determined by using a curve fitting software (TableCurve 2D, Jandel Scientific, San Rafael,

CA). The coefficient of determination (R^2) and the standard error (SE) were determined for the fitted models and they were used as criteria for selecting the best model. The goodness of fit of the tested mathematical models to the experimental data was evaluated from the coefficient of determination (R^2). The higher the R^2 value, the better the goodness of fit.

Color parameters

The color of the samples was measured using Hunterlab Color Analyzer (Hunter Associates Laboratory Inc., Reston, Virginia, U.S.A.). The chromacity of microwave-vacuum dried berries was determined by measuring their respective L , a and b coordinates. After initial calibration against standard black and white surface plates, four measurements for each sample were taken; L being the lightness indicator and a and b the chromacity coordinates. Color delta values, ΔL , Δa and Δb , were calculated according to the following equations:

$$\Delta L=L-L_t \quad (3)$$

$$\Delta a=a-a_t \quad (4)$$

$$\Delta b=b-b_t \quad (5)$$

where L , a and b are the measured values of the specimen and L_t , a_t , b_t are values of the target color. The target colors in the experiment are L , a and b of the fresh saskatoon berry fruit. The total color difference (ΔE_{ab}) is calculated using the L , a , b color coordinates and as defined by the Equation 6 [Maruyama *et al.*, 2001]:

$$\Delta E_{ab} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (6)$$

Water activity

Water activity (a_w) of the saskatoon berries was measured using a Pawkit water activity meter

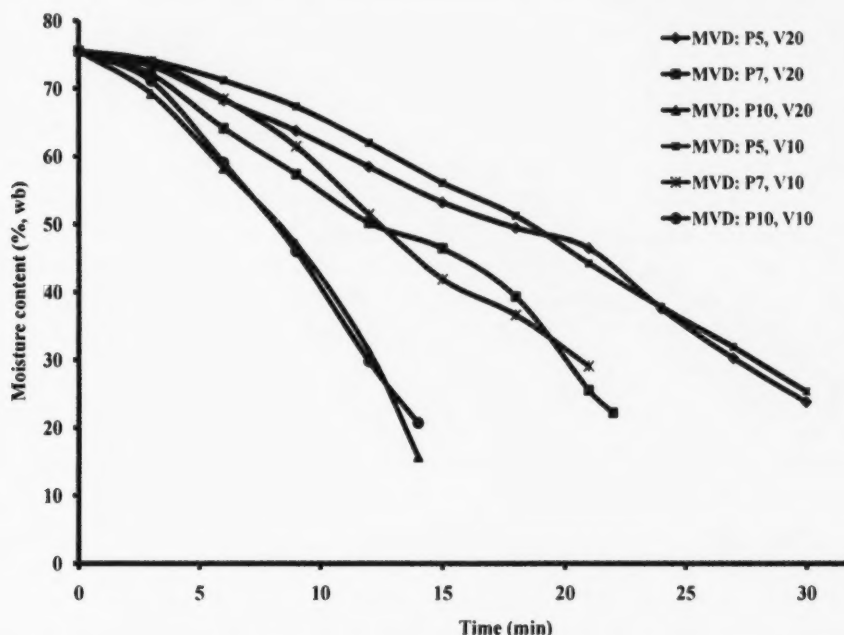


Figure 2. Drying curves of saskatoon berries at different of microwave power and vacuum pressure levels.

(Decagon Devices, Inc., Pullman, WA, U.S.A.). The instrument uses a dielectric humidity sensor to measure the a_w of a sample. The readings are accurate to $\pm 0.02 a_w$. Water activity is an index of the energy status of the water in a system. It is measured by equilibrating the liquid phase water in the sample with the vapour phase water in the headspace. Since temperature plays a critical role in water activity determinations, accuracy is best obtained when the sample is near room temperature. Two replicates were made for each sample and 3 readings for each replicate were taken and the mean was used for analysis to account for small variations in room temperature.

RESULTS AND DISCUSSION

Drying kinetics

Figure 2 shows the drying curves for microwave-vacuum drying of saskatoon berries at different microwave power and vacuum pressure levels.

The figure shows that the vacuum pressure did not influence the drying of the berries to any extent. The effect of system pressure on drying time was not as significant as that of microwave power. The figure also shows the effect of microwave power level on the drying characteristics of the berries during microwave-vacuum drying. The microwave power had a greater influence on the drying of the berries. A marked decline was noted in the drying time with an increase in microwave power level.

Drouzas and Schubert [1996] reported that vacuum pressure did not influence the microwave-vacuum drying of banana slices, however, microwave power level affected the drying of the slices.

The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of micro-

Table 1. Model parameters, standard error (SE), and coefficient of determination (R^2) of the drying models fitted to the microwave-vacuum drying data of saskatoon berries.

Microwave power (W)	Pressure (kPa)	Model parameters							
		MR = (a+bt) ²				MR = exp(m+nt ^{1.5})			
		a	b	R ²	SE	m	n	R ²	SE
745	33.5	1.015	-0.053	0.992	0.038	0.005	-0.049	0.999	0.016
(P10)	67.0	1.002	-0.053	0.999	0.015	-0.023	-0.049	0.995	0.029
514	33.5	1.025	-0.034	0.985	0.045	0.011	-0.024	0.995	0.025
(P7)	67.0	0.989	-0.032	0.985	0.042	0.011	-0.024	0.975	0.054
374	33.5	1.020	-0.024	0.995	0.024	-0.010	-0.014	0.998	0.014
(P5)	67.0	0.991	-0.024	0.989	0.033	-0.066	-0.015	0.978	0.047

wave power and resulted in a drop in the drying rate. Higher drying times were obtained at higher microwave output powers. Thus, the microwave output power had a crucial effect on the drying rate.

Modeling of saskatoon berry drying curves

Table 1 lists the model parameters obtained by application of polynomial and exponential models to the experimental drying data. The models provided a good fit for most of the experimental data points with values for the coefficient of determination greater than 0.970. The exponential model provided a better fit for the drying data at the lower vacuum pressure, with higher R^2 and lower SE compared to the polynomial model. On the other hand, the polynomial model provided a better fit for the drying data at the higher vacuum pressure.

A good agreement was found between the experimental and fitted values, which can be seen in Figure 3. The polynomial model provided a better fit for this microwave-vacuum drying condition. The exponential model under or over predicted the experimental values compared to the polynomial model.

Color parameters

The color parameters (**L**, **a**, **b**) for the saskatoon berries before and after drying, delta values (color change) and the total color difference are presented in Table 2. There were variations in the **L** and **a** values for the fresh berries. The differences in the **b** values for the fresh berries were not significant at 5% level. After drying, the samples did not show any significant variation in the **a** values. However, the samples exhibited some variations in the **L** and **b** values after drying. The **L** values of the samples after drying were higher than the fresh samples. The samples became lighter after drying. There were reductions in the **a** and **b** values after drying. The samples lost some of their reddish and yellowish color as presented in Table 2. The vacuum pressure and the microwave power levels did not significantly change the yellowness of the samples as indicated by the Δb values. Microwave-vacuum drying produced significant color changes in the **L** and **a** values as indicated by ΔL and Δa .

Total color difference was dependent on microwave power and vacuum pressure levels. Microwave-vacuum drying at 374 W and 67.0 kPa produced the lowest total color difference of 0.98. The highest ΔE_{ab} value of 4.91 was produced at microwave-vacuum drying 374 W

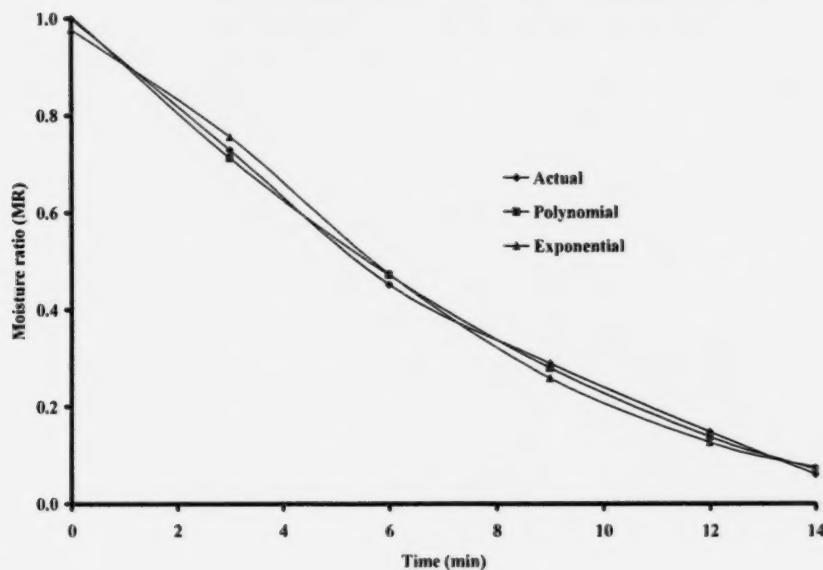


Figure 3. Predicted and experimental curves for microwave-vacuum drying at power level 10 and 67 kPa vacuum pressure.

Table 2. Comparison of color parameters for microwave-vacuum drying of saskatoon berries at various conditions of microwave power level and system pressure.

Microwave power level	Vacuum pressure (kPa)	Color parameters						Delta values			ΔE_{ab}
		Fresh berries			Dried Berries						
		L	a	b	L	a	b	ΔL	Δa	Δb	
P10	33.5	10.69a	3.84b	1.62a	13.23a	1.34a	0.54a	2.54abc	-2.50a	-1.09a	4.15b
P7	33.5	14.03b	3.00ab	1.57a	16.37b	1.99a	1.25bc	2.34abc	-1.02ab	-0.32a	3.32ab
P5	33.5	11.59a	3.10ab	1.87a	16.17ab	2.02a	1.19bc	4.58c	-1.08ab	-0.68a	4.91b
P10	67.0	16.21c	2.45ab	1.17a	15.30ab	1.72a	0.91ab	-0.92a	-0.73b	-0.26a	2.76ab
P7	67.0	14.02b	2.46ab	1.29a	18.07b	1.41a	1.15bc	4.05bc	-1.05ab	-0.14a	4.23b
P5	67.0	15.64bc	2.03a	1.48a	15.88ab	1.71a	1.36c	0.25ab	-0.32b	-0.12a	0.98a

L = brightness (+100)/ darkness (+0); a = redness (+50)/greenness (-50); b = yellowness (+50)/blueness (-50).

Mean values with the same letter in the same column are not significantly different at 5% level.

Table 3. Water activity values comparison of fresh and dried saskatoon berries.

Sample		Temperature (°C)	Water activity (a_w)	Moisture content (%)
Fresh berries		24.3	0.93 (0.01)	75.57
Microwave-vacuum drying				
Microwave power level	Pressure (kPa)			
P10	33.5	25.7	0.70	20.68
P10	67.0	26.0	0.66	15.68
P7	33.5	25.4	0.73	29.03
P7	67.0	25.8	0.75	25.49
P5	33.5	25.2	0.74	25.28
P5	67.0	26.0	0.61	23.75

and 33.5 kPa. This might be attributed to the longer drying time that was required to dry the sample.

Water activity

The change in water activity on microwave-vacuum drying of saskatoon berries under different experimental conditions is listed in Table 3. Water activity values of the samples were reduced from initial 0.93 to a range of 0.61 - 0.75. The highest a_w value of 0.75 was obtained at P7 and vacuum pressure of 67.0 kPa. There was no correlation between the moisture content and the water activity of the samples. In addition, temperature did not show any relationship with the water activity.

CONCLUSIONS

Microwave-vacuum drying of saskatoon berries was investigated at different power and vacuum pressure levels and the following conclusions were drawn:

The vacuum pressure levels did not greatly influence the drying time of the saskatoon berries compared to the microwave power levels. Increasing the microwave power level produced faster drying times for the samples. After 12 min of drying at power level 10, the moisture

contents of the samples at vacuum pressures of 33.5 and 67.0 kPa were 29.74 and 31.24%, respectively. However, after drying for 12 min at a vacuum pressure of 33.5 kPa, the moisture contents at power levels 10, 7 and 5 were 29.74, 51.41 and 61.95%, respectively.

Polynomial and exponential models were fitted to the drying data. The exponential model provided a better fit for the drying data at the lower vacuum pressure, with higher R^2 and lower SE compared to the polynomial model. On the other hand, the polynomial model provided a better fit for the drying data at the higher vacuum pressure.

The vacuum pressure and the microwave power levels did not significantly change the yellowness of the samples as indicated by the Δb values. However, microwave-vacuum drying produced significant color changes in the L and a values as indicated by ΔL and Δa . Total color difference was dependent on microwave power and vacuum pressure levels.

Water activity of the samples after drying ranged from 0.61 to 0.75 for moisture content range of 15.68 to 29.03%.

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